NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO
ATTN OF:

March 27, 1971

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General
Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned
U.S. Patents in STAR

In accordance with the procedures contained in the Code GP to Code USI memorandum on this subject, dated June 8, 1970, the attached NASA-owned U.S. patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No.	:	3,341,778
Corporate Source	:	Electrac, Inc.
Supplementary Corporate Source	:	
NASA Patent Case No.	:	XGS-00740

Please note that this patent covers an invention made by an employee of a NASA contractor. Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of Column No. 1 of the Specification, following the words ". . . with respect to an invention of. . . ."

G. Parker
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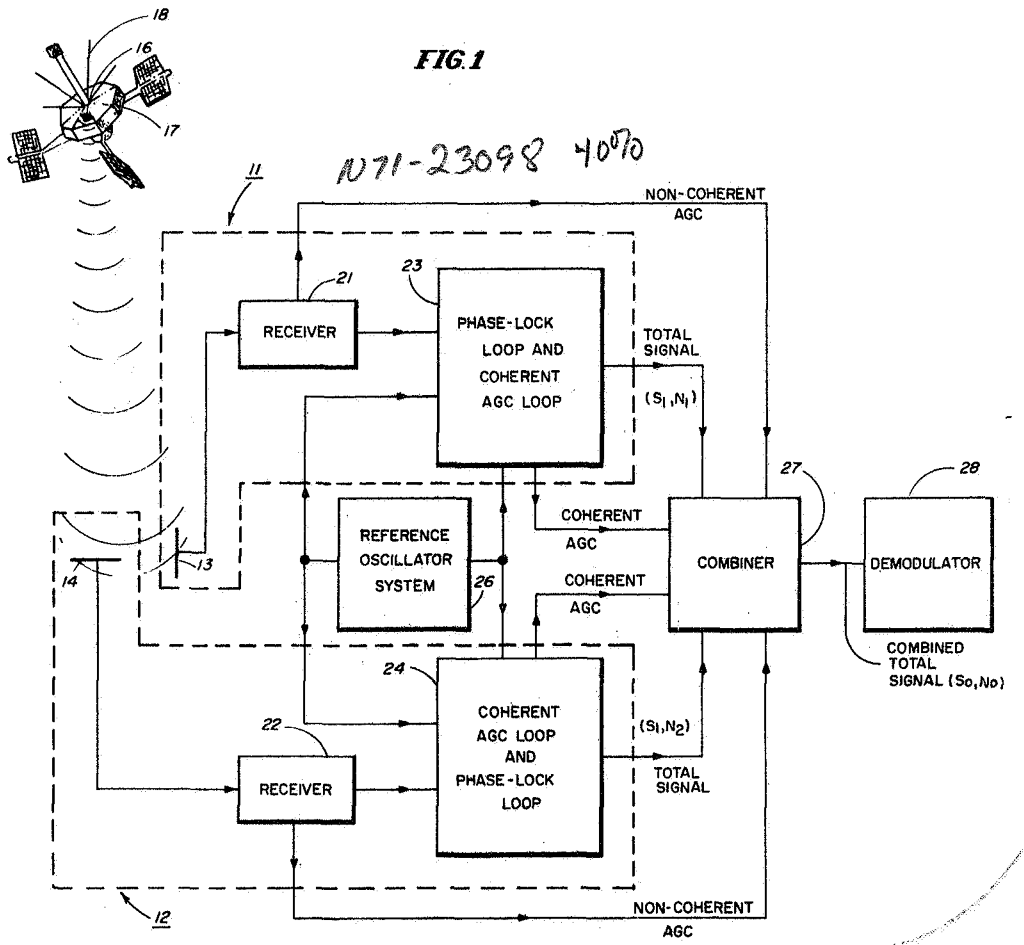
Enclosure:
Copy of Patent

N71-23098

FIG. 1



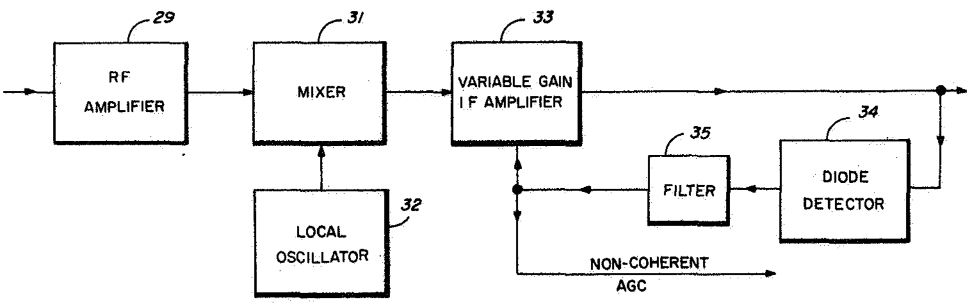


FIG. 2

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1361

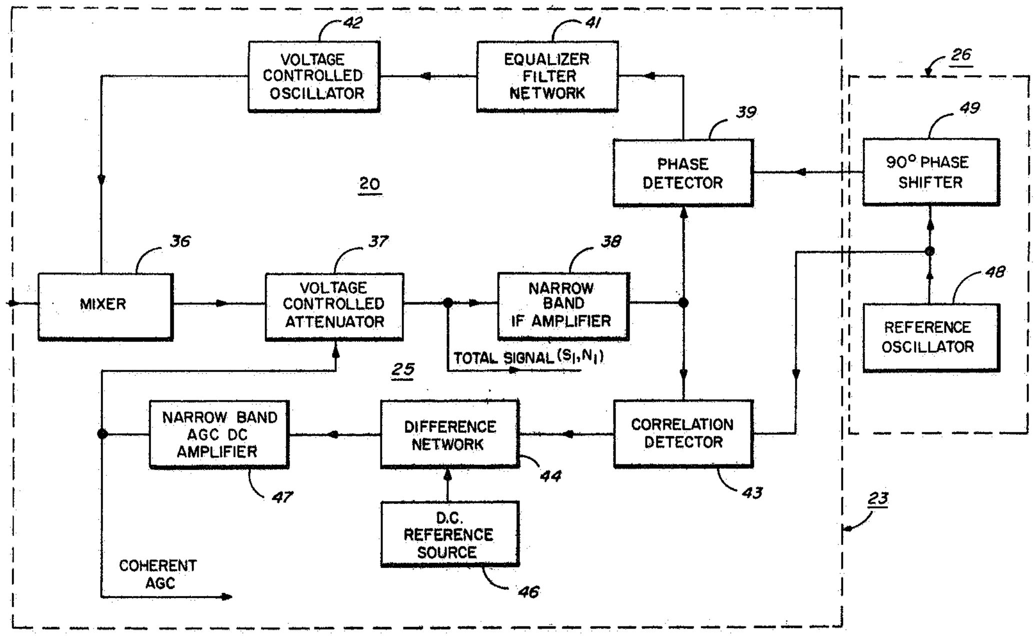
Sept. 12, 1967 HUGH L. DRYDEN 3,341,778

DEPUTY ADMINISTRATOR OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

OPTIMUM PRE-DETECTION DIVERSITY RECEIVING SYSTEM

Filed March 20, 1964 3 Sheets-Sheet 2

FIG. 3



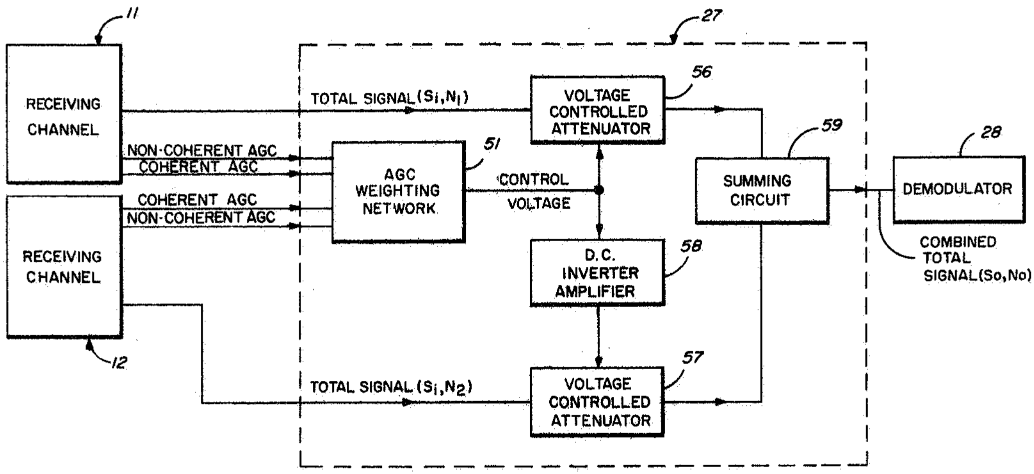


FIG. 4

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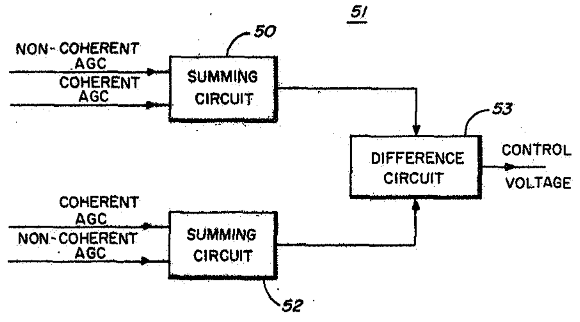

FIG. 5

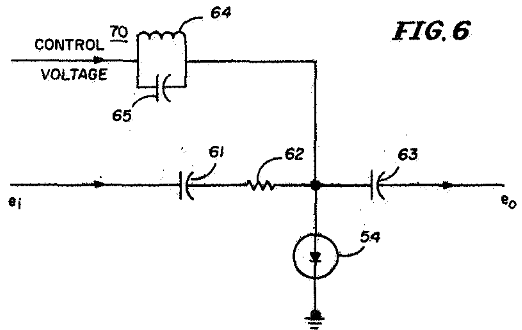

FIG. 6

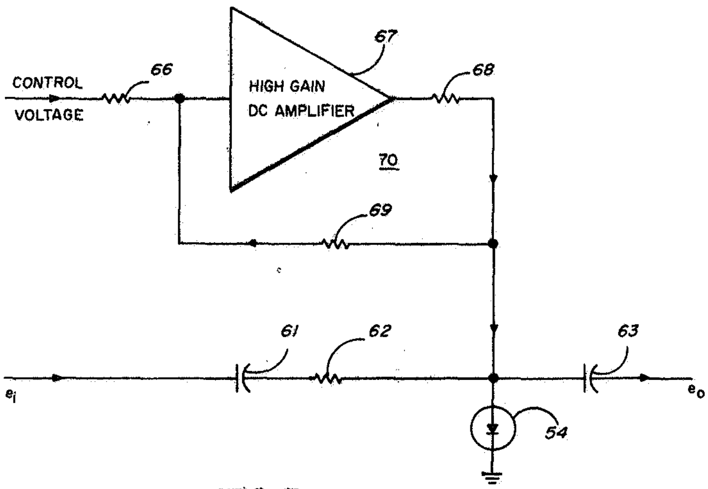

FIG. 7

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Patented Sept. 12, 1967

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3,341,778
OPTIMUM PRE-DETECTION DIVERSITY RECEIVING SYSTEM

Hugh L. Dryden, Deputy Administrator of the National Aeronautics and Space Administration, with respect to an invention of Louis Katz, Anaheim, and Raymond W. Honey, Fullerton, Calif., and Victor R. Simas, Lanham, Md.

Filed Mar. 20, 1964, Ser. No. 353,644
17 Claims. (Cl. 325—305)

ABSTRACT OF THE DISCLOSURE

Two independent diversity receiving channels, by action of automatic gain control (AGC) and phase-lock loops contained in each of the receiving channels, adjust the signals thereof so that the output intermediate frequency (IF) signals from both channels are equal in amplitude and phase coherent. The AGC voltages generated in each channel, in addition to controlling the level of the signal thereof, are measures of the signal to noise ratio (SNR) of the IF signal in the channel with which they are associated. The IF signals and the AGC voltages are applied to a novel combiner which includes two voltaged controlled attenuators (VCA's), and AGC weighting network, and a summing circuit. In the AGC weighting network the various AGC voltages are combined to produce a control voltage which is in turn applied to the VCA's. Also coupled to the VCA's are the IF signals from the respective channels associated therewith. The control voltage from the weighting network varies the attenuation ratios of the VCA's such that the IF signal having the smaller SNR is attenuated more than the IF signal having the greater SNR. The signals from the VCA's, after being summed in the summing circuit, are then applied to a demodulator.

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85–568 (72 Stat. 453; 42 U.S.C. 2457).

The present invention relates to a diversity receiving system, and, more particularly, to an optimum pre-detection diversity combining receiving system adapted for use with amplitude modulation (AM), phase modulation (PM) or narrow band frequency modulation (FM) systems.

Diversity receiving of radio signals is a well known method of reception applied with success to radio transmissions in order to minimize the fading effects. This principle is equally beneficial in reducing fading effects in spacecraft to ground communications wherein the fading may be due to the continuously changing polarization orientation of the received signal with respect to the receiving antenna. For instance, if the spacecraft transmitted signal polarization is linear and the ground antenna is polarized linearly, then as the spacecraft orientation changes, the level of the received signal can vary from zero to some maximum value. Two receiving antennas polarized orthogonally would be an application of the diversity concept and would assure a received signal close to optimum in at least one of the antennas as far as polarizaton effects are concerned. This diversity concept applies not only to linearly polarized radiation but to circular or elliptical as well.

In the various diversity receiving systems, there is always required some means for combining the signals to produce the best possible signal-to-noise ratio (SNR). Mr. Leonard R. Kahn in his article in the "Proceedings of the Institute of Radio Engineers" for November 1954, volume 42, on page 1705 describes a diversity combining system called the ratio-squarer system in which the optimum diversity combining law is utilized so that at all times the combined SNR is greater than or at least equal to the best of the individual diversity channel SNR.

The invention as will be described hereinafter, while using the ratio-squarer system to obtain optimum diversity combining, accomplishes the basic objectives more accurately than has been done in the past; and further, it has the additional feature of maintaining a constant output signal.

Accordingly, it is an object of the present invention to provide an improved and more accurate optimum diversity combining receiving system.

It is another object of the present invention to provide an improved optimum pre-detection diversity combining receiving system wherein the combined total signal has a maximum SNR and the output signal thereof is maintained constant.

It is still another object of the present invention to provide an improved optimum diversity combining system wherein the circuit design and electrical components are selected so that the combined total signal will have a maximum SNR and the combined signal thereof will be maintained exactly constant.

It is a further object of the present invention to provide an optimum diversity combining receiving system wherein precise optimum combining is accomplished prior to signal detection to eliminate certain deleterious effects.

These and other objects are carried out by the present invention in which the inputs of two independent receiving channels are derived from separate receiving antennas, which may be for example, cross polarized antennas and/or antennas located some distance apart. Since the receiving channels and the components thereof are chosen to be similar, the effective receiver noise voltages present in both receiving channels and associated with the signals thereof are substantially equal. The effective receiver noise voltage of each receiving channel is defined as the total receiver noise referred to the input terminals of the receiver and includes the internal noise produced by the initial stages of the radio frequency (RF) amplifier of the receiver and any noise fed to the receiver by the antenna. It should be noted that the inherent characteristics of the random noises in the two channels are a flat frequency characteristic and statistical independence.

Both of the receiving antennas received signals at the same frequency. However, variations of amplitude (signal strength) and phase (time of arrival) of the signals received by the two antennas may occur which result in their having an unpredictable amplitude difference and phase difference. To insure that the output signals from the two receiving channels are maintained equal in amplitude and phase coherent so that they can be properly combined, automatic gain control (AGC) and phase-lock means are provided in both receiving channels. While the signal portion of total signal (signal plus noise voltage associated therewith) from one receiving channel is modified to be identical with that from the other receiving channel, different values of additive white random noise are generally associated with each signal. For this reason therefore, each total signal usually has a different signal-to-noise ratio (SNR).

A novel combiner, as will be described in detail hereinafter, weights the sum of the two total signals through the action of two voltage controlled attenuators (VCA), having logarithmic characteristics, so that an output therefrom continually results in a constant sum and a maxi-

mum ratio of combined output signal-to-noise. The voltage controlled attenuators are controlled by AGC voltages, which bear a required relationship to the signal-to-noise ratio (SNR) in each of the two receiving channels wherein they are generated, so that the weaker of the two total signals is attenuated more while the stronger is attenuated less.

The necessary attenuation characteristics of the VCA's to provide the required two conditions to be met in the diversity combining system, i.e.,

(1) maximum output signal-to-noise ratio for all values of input noise and signal levels, and
(2) constant output signal level for all values of input noise and signal levels,

is derived below for the case under consideration in which the IF signals (S_i) applied to the VCA's are equal and phase coherent (by action of the AGC systems and phase-lock loops in the receiving channels), and the noise voltages (N_1, N_2) are statistically independent and generally unequal. Under these conditions it follows that the time averaged signal power (S_o^2) and the time averaged noise power ($\overline{N}_o^2$) from the combiner are:

$$S_o^2=(a_1+a_2)^2S_i^2=\text{constant} \qquad (1)$$

$$\overline{N}_o^2=a_1^2\overline{N}_1^2+a_2^2\overline{N}_2^2 \qquad (2)$$

where:

S_i=signal voltage from each receiving channel
N_1=effective noise voltage from one receiving channel
N_2=effective noise voltage from the other receiving channel
a_1=voltage attenuation ratio of attenuator associated with said one receiving channel
a_2=voltage attenuation ratio of attenuator associated with said other receiving channel
S_o=combined signal output from combiner
N_o=combined noise voltage output from combiner

The output signal-to-noise power ratio is then:

$$S_o^2/\overline{N}_o^2=\frac{(a_1+a_2)^2S_i^2}{a_1^2\overline{N}_1^2+a_2^2\overline{N}_2^2} \qquad (3)$$

Substituting equation (1) in equation (3) eliminates the term a_2 and provides the following identity:

$$S_o^2/\overline{N}_o^2=\frac{S_o^2}{a_1^2\overline{N}_1^2+(S_o/S_i-a_1)^2\overline{N}_2^2} \qquad (4)$$

Now proceeding to maximize the output signal-to-noise power ratio for constant output signal by differentiating both sides of Equation 4 with respect to a_1 and equating to zero; there is derived the following expression:

$$\frac{d(S_o^2/\overline{N}_o)^2}{da_1}=[-S_o^2a_1^2\overline{N}_1^2+(S_o/S_i-a_1)^2\overline{N}_2^2]^{-2}$$
$$[2a_1\overline{N}_1^2+2(S_o/S_i-a_1)(-1)\overline{N}_2^2]=0 \qquad (5)$$

Rewriting Equation 5 in a more simple form by eliminating the portion that cancels out, the following relationship is obtained:

$$2a_1\overline{N}_1^2+2(S_o/S_i-a_1)(-1)\overline{N}_2^2=0 \qquad (6)$$

$$a_1(\overline{N}_1^2+\overline{N}_2^2)=S_o/S_i\overline{N}_2^2 \qquad (7)$$

Now, solving for a_1:

$$a_1=\frac{S_o/S_i\overline{N}_2^2}{\overline{N}_1^2+\overline{N}_2^2}=\frac{S_o/S_i}{1+\overline{N}_1^2/\overline{N}_2^2} \qquad (8)$$

By rearranging the terms of the Equation 1 the following identity is obtained:

$$a_2=S_o/S_i-a_1 \qquad (9)$$

Now, by substituting Equation 8 in equation 9, a_2 then assumes the following relationship:

$$a_2=S_o/S_i-S_o/S_i\frac{\overline{N}_2^2}{\overline{N}_1^2+\overline{N}_2^2}=S_o/S_i\left(1-\frac{\overline{N}_2^2}{\overline{N}_1^2+\overline{N}_2^2}\right) \qquad (10)$$

$$a_2=S_o/S_i\frac{\overline{N}_1^2}{\overline{N}_1^2+\overline{N}_2^2}=\frac{S_o/S_i}{1+\overline{N}_2^2/\overline{N}_1^2} \qquad (11)$$

Accordingly, the values of a_1 in Equation 8 and a_2 in Equation 11 are the required attenuation ratios necessary for satisfying the two specified diversity combining system conditions set out above. An attenuator which can satisfy each of these equations will be described in detail hereinafter.

The exact nature of this invention, as well as other objects and advantages thereof, will be readily apparent from consideration of the following specification relating to the annexed drawings in which:

FIGURE 1 shows a block diagram of the preferred optimum pre-detection diversity combining receiving systems of the present invention;

FIGURE 2 shows a block diagram of the receiver portion of FIGURE 1;

FIGURE 3 depicts a block diagram of the phase-lock and coherent AGC loops and reference oscillator system of FIGURE 1;

FIGURE 4 shows a block diagram of the novel combiner of FIGURE 1;

FIGURE 5 illustrates a block diagram of the AGC weighting network of FIGURE 4; and

FIGURES 6 and 7 depict schematic diagrams of two embodiments of the voltage controlled attenuators (VCA) of FIGURE 4.

Referring now to the drawings, wherein like reference characters designate like or corresponding parts throughout, there is shown in FIGURE 1 an optimum pre-detection combining diversity receiving system comprising two independent receiving channels **11**, **12** having substantially equal effective receiver noise voltages at the input terminals thereof and having antennas **13**, **14**, respectively cross-polarized. A beacon transmitter **16** located in either a stationary object or a moving object such as spacecraft **17** radiates a linearly polarized signal from radiating antenna **18**. By antennas **13**, **14** being cross-polarized, the diversity receiving system is assured of receiving the transmitted signal even if its polarization might vary, as for example, when spacecraft **17** is moving and radiating antenna **18** varies in position relevant to receiving antennas **13**, **14**. While there is always the assurance that the transmitted signal will be picked up by antennas **13**, **14**, as already mentioned above, a time variation of the amplitude and phase thereof will usually result in the signals received by receiving channels **11**, **12** having unpredictable phase differences and amplitude differences.

To modify the received signals so that these differences no longer exist and, in fact, so that the signals are equal in amplitude and coherent in phase, the conditions essential for them to be properly combined, receiving channels **11**, **12**, as shown in FIGURE 1, include, in addition to antennas **13**, **14**, heterodyning receivers **21**, **22** and phase-lock and coherent automatic gain control (AGC) loops **23**, **24**, respectively. A reference oscillator system **26** is connected to phase-lock and coherent AGC loops **23**, **24** to assist these loops in modifying the intermediate frequency (IF) signals applied thereto from receivers **21**, **22**, respectively, so that they become equal to the reference signal frequency.

Since both receiving channels **11**, **12** are identical and operate in the same manner, the following discussion, while relating to receiving channel **11**, applies equally as well to receiving channel **12**. Receiver **21**, as shown in detail in FIGURE 2, comprises a wide-band radio frequency (RF) amplifier **29** to which is fed the RF total signal picked up by antenna **13**. A mixer **31** is connected to the wide-band RF amplifier **29** and to a local oscillator **32** to heterodyne the RF total signal from the RF amplifier **29** with the signal from local oscillator **32**. This provides an IF total signal which is coupled to a variable gain IF amplifier **33**. A conventional diode detector **34**

and series low pass filter **35** are connected from the output of variable gain IF amplifier **33** to an input thereof to act as an automatic gain control (AGC) for variable IF amplifier **33** by applying a non-coherent (AGC) voltage thereto. In this manner the IF total output signal (signal and effective noise voltage associated therewith) from variable gain IF amplifier **33** is maintained at a fixed level. This non-coherent AGC voltage is a measure of the receiver SNR in that it is proportional to the logarithm of the SNR due to the fact that the components of the variable gain IF amplifier are chosen so that it has a logarithmic characteristic.

For all receiver signal levels where the SNR of the receiver signal is less than unity, the output total signal from variable gain IF amplifier **33** contains, essentially, a constant noise amplitude and therefore, the non-coherent AGC voltage is a measure of the noise only and independent of the signal which is assumed to vary in amplitude. On the other hand, should the SNR of the receiver signal be greater than unity then the output of variable gain IF amplifier **33** contains a constant output signal amplitude and is independent of noise. The non-coherent AGC voltage is then a measure of signal only and consequently also of the SNR in the receiver since the noise is constant.

The coherent AGC voltages to be discussed in connection with FIGURE 3 and the IF total output signals from phase-lock and coherent AGC loops **23, 24,** along with non-coherent AGC voltages from receivers **21, 22** are applied to a novel combiner **27** (to be described in detail hereinafter in connection with FIGURES 4–7). In the combiner **27** the IF total signals are weighted, according to their respective signal-to-noise ratios (SNR), prior to combining so that the one having the lowest SNR has less effect upon the SNR of the combined IF signal. Accordingly, by the performance of the weighting action in combiner **27,** the combined total signal output therefrom, has a maximum SNR for all values of the signals acquired by antennas **13, 14** and is applied to demodulator **28.** In addition, the combined total signal output (S_o) from combiner **27** is constant for all the values of the signals received by antennas **13, 14,** and at the same time is always equal to the IF signal (S_i) derived from either of the receiving channels **11, 12,** i.e., $S_o=S_i=$constant.

Phase-lock and coherent AGC loops **23** are shown in FIGURE 3 as comprising a phase-lock loop **20** and coherent AGC loop **25.** Phase-lock loop **20** includes mixer **36,** voltage controlled attenuator (VCA) **37** (to be described in detail hereinafter), IF narrow-band amplifier **38,** phase detector **39,** equalizer filter network **41** and voltage controlled oscillator (VCO) **42,** all connected as shown. The total signal output from variable gain IF amplifier **33** of receiver **21,** after being applied to mixer **36** of this loop, has the frequency and phase of the carrier portion of the signal thereof adjusted by the loop so that when it is applied from VCA **37** to combiner **27** it will be phase coherent with its counterpart of the signal applied to combiner **27** from the VCA of receiving channel **12.**

Coherent AGC loop **25,** in addition to including VCA **37** and narrow-band IF amplifier **38** of phase-lock loop **20,** also includes correlation detector **43,** difference network **44,** DC reference source **46** and AGC DC amplifier **47,** all connected as shown. Coherent AGC loop **25** controls the amplitude of the signal from VCA **37** so that it will be constant and equal to its counterpart signal taken from the VCA of receiving channel **12.** Accordingly, by the action of these two loops in conjunction with reference oscillator system **26,** the operation of which will be described in detail hereinafter, the signal (S_i) of receiving channel **11** is modified to be identical in amplitude and coherent in phase with its counterpart signal (S_i) obtained from receiving channel **12.**

The following is a description of the operation of phase-lock loop **20.** The IF signal from variable gain amplifier **33,** and the output of VCO **42** are applied to mixer **36** and heterodyned therein; and the heterodyned output signal from mixer **36** is thereafter attenuated by VCA **37** and amplified by narrow-band IF amplifier **38** to establish both the level and band width of the signal applied thereto. The output signal from narrow-band IF amplifier is coupled to phase detector **39,** which is a balanced product detector. Also coupled to phase detector **39** is an output signal from reference oscillator **48** of reference oscillator system **26,** after the reference oscillator signal has been shifted 90 degrees by a 90 degree phase shifter **49.** The quadrature relationship between the carrier component of the signal from narrow-band IF amplifier **38** and the signal from reference oscillator **48** causes phase detector **39** to produce a DC voltage output proportional to the phase difference (off quadrature) between the two signals. This DC voltage is fed via equalizer filter network **41,** a low pass filter circuit, as a smoothed DC voltage to voltage controlled oscillator (VCO) **42** to control the frequency thereof such that phase coherence is maintained between the 90 degrees shifted signal from reference oscillator system **26** and the carrier component of the IF signal from narrow-band IF amplifier **38.** In this manner the frequency of the signal from VCO **42** tracks the frequency of the carrier component of the IF signal applied from variable gain IF amplifier **33** to mixer **36.** Thus, with these signals changing frequency simultaneously and in-phase, the output level of phase detector **39** tends to approach zero.

One example of VCO **42** would be a Colpitt's oscillator in which the inductor of the tank circuit is a saturable reactor. By controlling the current flow through this reactor, the oscillator frequency, which can be made a linear function of the control current flowing through the reactor, is controlled over its designed frequency range.

While the above description appears to indicate that the DC voltage from phase detector **39** is only proportional to the phase relationship between the 90 degrees shifted signal of reference oscillator system **26** and the carrier component of the IF signal from narrow-band IF amplifier **38,** this is not absolutely correct since this DC voltage is also proportional to the amplitude of the carrier component of the IF signal from narrow-band IF amplifier **38.** The reason that the amplitude of the carrier component was neglected in the above discussion, was due to the fact that it was maintained constant by coherent AGC loop **25.** This coherent AGC loop supplies an AGC DC control voltage to VCA **37** to adjust the attenuation thereof so that the carrier component of the IF signal applied to phase detector **39** of phase-lock loop **20** is maintained at a constant amplitude. This VCA has a characteristic such that the logarithm of attenuation is precisely linear with the DC control voltage applied thereto as further explained below.

The following is a description of the operation of AGC loop **25.** The carrier output component of the IF signal from IF amplifier **38,** in addition to being applied to phase detector **39,** is also applied, along with the direct output from reference oscillator **48,** to correlation detector **43,** a balanced product detector which is a circuit well known in the art. Since the reference signal and carrier component of the IF signal from IF amplifier **38** have already been phase locked in quadrature by the phase-lock loop **20,** the signals applied to the correlation detector are in-phase and the AGC DC output from correlation detector **43** is then proportional to the amplitude of the carrier component of the IF signal. Correlation detector **43** is so designed that its output is independent of the reference signal input level. The noise voltage accompanying the input signal produces a fluctuation of the DC output from correlation detector **43.** This fluctuation is smoothed by the narrow band AGC DC amplifier **47** after the DC voltage output from correlation detector **43** has been compared (subtracted) with a fixed DC voltage

from reference source **46** in difference network **44**. The difference comparison between the DC voltage output from correlation detector **43** and the DC voltage of reference source **46** is carried out so that VCA **37** will operate in the proper portion of its control range by the application of the AGC voltage applied thereto from AGC amplifier **47**. The smoothed, substantially noise free AGC DC voltage from AGC amplifier **47** is then applied to VCA **37** to control the attentuation thereof so that the carrier component of the IF signal, coupled from narrow-band IF amplifier **38** to phase detector **39**, is maintained constant. The phase-lock loop dynamics are thus made relatively independent of the input signal level over the operating range of the AGC system.

The total signal from VCA **37**, in addition to being coupled to narrow-band IF amplifier **38**; and the coherent AGC voltage from narrow-band AGC DC amplifier **47**, in addition to being applied to VCA **37**, are both coupled, along with the non-coherent AGC voltage from diode detector **34** of receiver **21**, to combiner **27** as shown in FIGURES 1 and 4.

While the above description relates to only one receiving channel **11**, it should be understood that the other receiving channel **12**, in cooperation with reference oscillator system **26**, operates in the same manner so that the output signal from the VCA of these phase-lock and coherent AGC loops **24** has the same amplitude as the signal from VCA **37** and is phase coherent therewith. The total signal from the VCA of the phase-lock and coherent AGC loops **24**, the coherent AGC voltage from the coherent AGC loop thereof, and the non-coherent AGC voltage from receiver **22** are applied, along with their counterparts in receiving channel **11**, to combiner **27**.

Combiner **27**, as shown in FIGURE 4, includes AGC weighting network **51** to which is applied the AGC voltages from receiving channels **11, 12**; a DC inverter amplifier **58** coupled to AGC weighting network **51**; voltage controlled attenuator (VCA) **56**, to which is coupled the total signal from receiving channel **11** and the combined AGC output from AGC weighting network **51**; voltage controlled attenuator (VCA) **57** to which is coupled the total signal from receiving channel **12** and the combined AGC output from AGC weighting network **51** via inverter amplifier **58**; and summing circuit **59** to which is applied the attenuated total signals from VCA's **56, 57**. This combiner, as will be described in more detail hereinafter, fulfills the previously derived optimum combining requirements by controlling the attenuation of the two total signals from receiving channels **11, 12** such that the poorer quality total signal is attenuated more while the superior quality total signal is attenuated less. In this manner the combined total signal quality (SNR) is always equal to or better than the total signal quality from either of the two receiving channels and can, in fact, be better than either total in SNR by as much as 3 decibels (db).

AGC weighting network **51** of combiner **27**, as shown in FIGURE 5, comprises summing circuits **50** and **52**, of the type well known in the art, to which are applied the non-coherent AGC and coherent AGC voltages of receiving channels **11, 12**, respectively; and difference circuit **53** to which is coupled the summed AGC outputs from summing circuits **50, 52**.

Assuming, as has been done herein, that the signal levels are varying because of the ever-changing polarization of the input signals and that both receiving channels **11, 12** have equal effective receiver noise voltages at their input terminals, then the non-coherent AGC voltages developed in both receivers of the receiving channels, where the SNR's are greater than unity, are measures in (db) of the SNR's of their respective receiving channels. Since the non-coherent AGC circuits act to provide substantially constant signal levels in the phase-lock and AGC loops **23, 24**, the coherent AGC voltages developed in their coherent AGC loops are essentially constant. Now, should the receiving channels have SNR's less than unity, then the outputs from the receivers are substantially constant noise voltages and the non-coherent AGC voltages are essentially constant. In this case, since the coherent AGC's function to provide constant signal levels in their respective receiving channels, they are measures, in db, of the SNR's of the receiving channels.

Accordingly, by AGC weighting network **51** summing the non-coherent and coherent AGC voltages of each receiving channels **11, 12** in summing circuit **50**, and **52**, respectively, and subtracting the outputs from the summing circuits in difference circuit **53**, the output from the difference circuit is a control voltage that is an accurate measure, in db, of the relative signal-to-noise ratios for the two receiving channels under all conditions of input signals and noise. This weighting network **51** is in effect a special analog computer wherein DC voltages proportional to the logarithm (decibel) are added and subtracted to provide a DC voltage proportional to the logarithm of product and quotient, respectively.

The control voltage from difference circuit **53** of AGC weighting network **51** is applied directly to VCA **56** and through a DC inverter amplifier **58** to VCA **57**. Applied to the inputs of VCA **56, 57** are the total signals from receiving channels **11, 12**, respectively. With the control voltage from difference circuit **53** being applied to VCA's **56, 57** in the manner just described, the attenuations of the VCA's are adjusted so that, in effect, as the total signal output from one VCA increases that from the other decreases. Accordingly, should the signal level of receiving channel **11** be higher than that from receiving channel **12**, then the output from difference circuit **53** is positive and the attenuation of VCA **56** is reduced and that of VCA **57** is increased. An opposite effect on VCA's **56, 57** occur when the signal level of receiving channel **12** is higher. In this manner, when the output signals from VCA **56, 57** are applied to summing circuit **59** and added therein, a signal S_0 is developed therefrom that is always constant. In addition, the combined total signal therefrom, that is applied to demodulator **28**, has a SNR equal to or greater than the SNR existing in either of the two receiving channel signals.

Referring now to FIGURES 6 and 7, the preferred embodiments of VCA **56, 57**, there is shown a high conductance logarithmic silicon diode **54** having one end thereof grounded and the other end connected to an input circuit comprising a series combination of DC blocking capacitor **61** (low AC impedance) and resistor (R) **62**. Also connected to the other end of the diode **54** is an output circuit including a DC blocking capacitor **63** (low AC impedance). The VCA's, shown in FIGURES 6 and 7, are identical except for the control signal feeding circuit **70**. In FIGURE 6, control signal feeding circuit **70** includes a parallel combination of inductor **64** and capacitor **65**; and in FIGURE 7 it includes a series combination of resistor **66**, high gain DC amplifier **67** and resistor **68**, and, in addition, feedback resistor **69**. In both the VCA's the total signal obtained from the receiving channel, with which the particular VCA is associated, is applied to capacitor **61** thereof, and the attenuated total signal from the VCA is coupled via capacitor **63** to summing circuit **59**.

In FIGURE 6, the DC control voltage derived from AGC weighting network **51**, shown in FIGURE 5, is applied to the VCA via the parallel combination of inductor **64** and capacitor **65**, which combination has a high AC impedance and a low DC impedance. This control voltage is applied to diode **54** to vary its impedance. The high AC impedance of the parallel combination of inductor **64** and capacitor **65** prevents the total signal from feeding into AGC weighting circuit **51**. Diode **54** has a logarithmic characteristic and has its impedance varying in accordance with the DC control voltage applied thereto from AGC weighting network **51**. This will cause the VCA to attenuate the total input signal applied to the diode in a logarithmic fashion as indicated by Equation 12.

The attenuator of FIGURE 7 operates in the same manner as that of FIGURE 6 except that the DC control voltage is applied through resistor **66** to high gain DC amplifier **67**. This control signal feeding circuit has a high impedance value for an AC signal in comparison with resistor **62**. Feedback resistor **69**, high gain DC amplifier **67** and resistor **66**, insure a precise DC voltage across diode **54** linear with the DC control voltage applied thereto regardless of the DC resistance of diode **54**. Since amplifier **67** has a high gain for DC voltages, the DC impedance of the circuit is reduced sufficiently to permit the DC control voltage from AGC weighting network **51** to be applied to and control the impedance of diode **54** so that the total signal applied thereto via blocking capacitor **61** and resistor (R) **62** is attenuated to a proper value before being passed to summing circuit **59**.

It is important to note that with diode **54** connected in the VCA in the polarity shown in FIGURES 6 and 7, a positive control voltage applied to diode **54** reduces its impedance, thereby increasing the attenuation of the VCA to reduce the output signal therefrom. Alternatively, a negative control voltage applied to diode **54** increases the diode impedance, and, accordingly, causes a reduction in the attenuation of the VCA. Since the DC control voltage is applied to VCA's **56**, **57** in an opposite polarity due to the inverter **58**, that is, there is applied a positive DC control voltage to one VCA and a negative DC control voltage to the other VCA, diode **54** is connected to have the same polarity in the two voltage controlled attenuators. On the other hand, if DC inverter amplifier **58** was omitted, the diodes **54** would be connected in a reverse polarity in the two VCA's, i.e., e.g., the diodes of the VCA shown in FIGURES 6 and 7 would be connected as shown when used as VCA **56** and would be connected in reverse polarity when used as VCA **57**. By the diodes in the two VCA's being connected in this manner, except when the AGC voltage inputs to difference circuit **53** are equal, one VCA will always be attenuating more than the other.

The following mathematical analysis applies equally as well to VCA's circuit of either FIGURES 6 and 7 and indicates how the VCA's fulfill the requirements set out hereinabove in Equations 8 and 11. Each VCA comprises, essentially, an ordinary fixed resistor (R) **62** and a silicon diode **54** whose alternating current (AC) resistance is characteristically a logarithmic function of the DC control voltage (E) applied via control signal feeding circuit **70**. The small-signal AC resistance (R_s) of the silicon diode **54** varies logarithmically as a function of the control voltage and is defined as follows:

$$R_s=R_o10^{-K_1E} \qquad (12)$$

where:

K_1 and R_o are diode constant parameters describing diode **54**, and, specifically, R_o is the value of the AC resistance for zero voltage control, and E is the DC control voltage applied to diode **54**.

The voltage gain of the VCA is:

$$a=e_o/e_i=\frac{R_s}{R+R_s}=\frac{1}{1+R/R_s} \qquad (13)$$

Now, substituting Equation 12 in Equation 13 the following expression is obtained:

$$a=\frac{1}{1+(R/R_o)10^{K_1E}}=\frac{1}{1+10^{K_1E+\log(R/R_o)}} \qquad (14)$$

Since the summed AGC DC voltages from each receiving channel is linearly proportional to the signal-to-noise ratio in db, it therefore follows that the ratio of the time averaged signal power to the time averaged noise power of the two receiving channels can be defined as follows:

$$P_1=S_1^2/\overline{N}_1^2 \qquad (15)$$

and

$$P_2=S_1^2/\overline{N}_2^2 \qquad (16)$$

The difference in the summed AGC DC voltages from the two receiving channel obtained from the AGC combining network expressed as a log function of the voltage is as follows:

$$E=K_2(10\log P_2)-K_2(10\log P_1)=K_2 10\log P_2/P_1 \qquad (17)$$

where:

K_2 is a proportionality constant which relates DC volts to db,

E is the DC control voltage applied to the silicon diode of the VCA's from the AGC combining network,

P_1 and P_2 are defined by Equations 15 and 16, respectively, and

$K_2(10\log P_1)$ and $K_2(10\log P_2)$ are the voltages from summing circuits **50** and **52**, respectively.

Now, substituting Equations 15 and 16 into Equation 17 the following identity is obtained:

$$E=K_2 10\log(S_1^2/\overline{N}_2^2)(\overline{N}_1^2/S_1^2) \qquad (18)$$
$$=K_2 10\log\overline{N}_1^2/\overline{N}_2^2$$

Then, substituting Equation 18 in Equation 14 a_1 becomes:

$$a_1=\frac{1}{1+10^{K_1K_2 10\log\overline{N}_1 2/\overline{N}_2 2+\log(R/R_o)}} \qquad (19)$$

and since the control voltage applied to the other VCA is of opposite polarity, then a_2 becomes:

$$a_2=\frac{1}{1+10^{-K_1K_2 10\log\overline{N}_1 2/\overline{N}_2 2+\log(R/R_o)}} \qquad (20)$$

Now, by *requiring that:*

$$K_2=\tfrac{1}{10}K_1$$

and also that

$$R=R_o$$

it is discovered that Equations 19 and 20 reduce to:

$$a_1=\frac{1}{1+\overline{N}_1^2/\overline{N}_2^2} \qquad (19')$$

and

$$a_2=\frac{1}{1+\overline{N}_2^2/\overline{N}_1^2} \qquad (20')$$

respectively.

Since the diversity system, as described hereinabove, has been designed so that $S_o=S_i=$constant, or $S_o/S_i=1$ then Equations 8 and 11 above reduce to:

$$a_1\frac{1}{1+\overline{N}_1^2/\overline{N}_2^2} \qquad (8')$$

and

$$a_2=\frac{1}{1+\overline{N}_2^2/\overline{N}_1^2} \qquad (11')$$

Now, comparing Equations 19′ and 20′ with Equations 8′ and 11′ respectively, it can be readily noted that they are identical. Accordingly, the VCA's of FIGURES 6 and 7 satisfy the system conditions set out hereinabove, and the diversity combining system described herein can be considered to be a truely optimum pre-detection diversity combining system.

In an operative embodiment of the voltage controlled attenuator of FIGURE 7—wherein the input signal (e_i) applied thereto was at a frequency of .5 megacycle and has a voltage as high as .1 volt peak, but was generally much less than 10 millivolts; the control voltage (E) applied to diode **54** was between .6 and .8 volt DC over a 50 db range; silicon diode **54** was a Texas Instruments, Incorporated type G–130 (commonly referred to as a stabistor); and high gain DC amplifier had substantially zero gain at .5 megacycles and 50,000 gain at DC—the values of the various components thereof were as follows:

Capacitor **61**	microfarad	.08
Capacitor **63**	do	.08
Resistor **66**	kilohms	50
Resistor **68**	do	50
Resistor **69**	do	50
Resistor **62** (R)	ohms	510

Diode **54** had small-signal AC resistance R_s from 10 ohms to 500 ohms depending upon the value of DC control voltage (E) applied thereto according to relationship of Equation 12, and R_o was equal to 510 ohms.

While the VCA's shown in FIGURES 6 and 7 have been described in connection with combiner **27**, the same VCA's are used in the phase-lock and AGC loops **23**, **24**. However, there they are biased to operate over a different portion of the control range (i.e., different range of E), as will now be shown. If in Equation 14 above:

$$10^{K_1E+\log(R/R_o)} \gg 1$$

then the attenuation in db is:

$$20 \log a = -20 \, [K_1E + (\log R/R_o)]$$

Noting that R/R_o is a constant, it can be seen that the attenuation expressed in db is linear with E (in this case the coherent AGC voltage). Because, as mentioned hereinabove, the effective receiver noise in each receiving channel is assumed to be equal, then the attenuation in db is proportional to the SNR. Thus, the coherent AGC voltage is a measure of the SNR as required in the combiner.

It is to be understood, that while the invention has been described in connection with the receiving station being ground located and having only two receiving channels, it is not limited to ground use nor to two channel operation, as it can function equally as well in a spacecraft and in connection with more than two receiving channels. For example, with a four (4) channel diversity system, the channels would be divided into pairs, each of the pairs to function in the manner described hereinabove to provide an optimum combined signal. Then, the output signals from the two combiners would themselves be processed in the same manner as discussed hereinabove in connection with the signals received by the two receiving antennas.

Although the foregoing disclosure relates to preferred embodiments of the invention, it should be understood that numerous modifications or alterations may be made therein without departing from the spirit and scope of the invention as set forth in the appended claims. For example, instead of a separate local oscillator being used with each receiver, a single oscillator can be used as a common local oscillator for both receivers.

What is claimed is:

1. The diversity receiving system having first and second receiving channels for use in a diversity reception system for receiving a transmitted signal, said diversity receiving system comprising: first receiving means included as part of said first receiving channel for receiving said transmitted signal and maintaining it and any noise voltage associated therewith at a constant level; second receiving means included as part of said second receiving channel for receiving said transmitted signal and maintaining it and any noise voltage associated therewith at a constant level; first phase adjusting and amplitude controlling means connected to said first receiving means, forming part of said receiving channel and including phase-lock means and automatic gain control means, said automatic gain control means providing an automatic gain control voltage; second phase adjusting and amplitude controlling means connected to said second receiving means, forming part of said second receiving channel and including phase-lock means and automatic gain control means, said automatic gain control means providing an automatic gain control voltage; reference oscillator means connected to said first and second phase adjusting and amplitude controlling means and cooperating therewith so that said phase-lock means and said automatic gain control means thereof function to provide signals from said receiving channels that are phase coherent and equal in amplitude; and combining means connected to said first and second phase adjusting and amplitude controlling means including weighting means for receiving the output signals from said phase adjusting and amplitude controlling means and said automatic gain control voltages from said automatic gain control means thereof and for weighting said output signals in accordance with said automatic gain control voltages so that the signal from said receiving channel having the lower signal-to-noise ratio is attenuated more than the signal from said receiving channel having the higher signal-to-noise ratio, and a summing means for combining said weighted signals and having as an output a constant signal having a signal-to-noise ratio equal to or greater than the signal-to-noise ratio of either of said receiving channel signals.

2. The diversity system of claim **1** wherein said phase-lock means of said first and second phase adjusting and amplitude controlling means are substantially the same and each includes a phase detector for comparing the phase of the incoming signal applied to the respective phase adjusting and amplitude controlling means with that of the signal from said reference oscillator means; a voltage controlled oscillator connected to said phase detector and having the frequency of its signal varied in accordance with the output from said phase detector; and a mixer connected to receive said incoming signal and said signal from said voltage controlled oscillator, whereby variations in phase of the incoming signal from that of the signal from said reference oscillator means results in a voltage being applied to said voltage controlled oscillator which in turn permits the voltage controlled oscillator to track the incoming signal and lock the output from said mixer to a signal at a desired frequency.

3. A diversity system of claim **2** wherein said automatic gain control means of said first and second phase adjusting and amplitude controlling means are substantially the same and each includes a correlation detector having the incoming signal from said phase adjusting and amplitude controlling means with which it is associated and said signal from said reference oscillator means applied thereto, said correlation detector detecting any variations in the amplitude of the said incoming signal and generating an automatic gain control voltage which is a measure of said variations in amplitude of said incoming signal from a desired value; and voltage controlled attenuating means connected to receive said incoming signal and having a control element; said voltage controlled attenuating means having applied thereto the output from said correlation detector, whereby the attenuation of the said voltage controlled attenuating means is varied in accordance with the signal applied thereto from said correlation detector such that said incoming signal applied to said voltage controlled attenuator means is attenuated and obtained as a constant amplitude output signal therefrom.

4. The diversity system of claim **3** wherein said weighting means comprises a difference circuit having applied thereto the automatic gain control voltages derived from said automatic gain control means of said first and second receiving channels, said difference circuit having as an output therefrom a control voltage which is a measure of the relative signal-to-noise ratios of the signals applied to said first and second receiving channels; first and second voltage controlled attenuators having applied to the inputs thereof the signals from said first and second receiving channels, respectively, and having connected to their control elements said control voltage, the outputs from said attenuators being applied to said summing means, whereby said voltage controlled attenuators are controlled such that the one having applied thereto the stronger signal-to-noise ratio signal is attenuated less and the one having the

weaker signal-to-noise ratio is attenuated more and the output signal from said summing means is at a constant amplitude and has a maximum signal-to-noise ratio.

5. The diversity receiver of claim **4** wherein the attenuation ratios of said first and second voltage controlled attenuators have the following identities:

$$a_1=\frac{S_o/S_i}{1+\overline{N}_1^2/\overline{N}_2^2}$$

and

$$a_2=\frac{S_o/S_i}{1+\overline{N}_2^2/\overline{N}_1^2}$$

respectively, where:

a_1=voltage attenuation ratio of said first voltage controlled attenuator
a_2=voltage attenuation ratio of said second voltage controlled attenuator
S_o=output signal from said summing means
S_i=signal voltage from either of said receiving channels
$\overline{N}_1^2$=time average effective noise power from said first receiving channel
$\overline{N}_2^2$=time average effective noise power from said second receiving channel.

6. The diversity system of claim **3** wherein said first and second receiving means each includes a variable gain intermediate frequency amplifier and an automatic gain control circuit for cooperating therewith to keep the output from said amplifier at a constant level; wherein each of said receiving channels has associated therewith a summing circuit to which is applied the automatic gain control voltage developed in the respective receiving channel; and wherein said weighting means includes a difference circuit for receiving the summed AGC voltages from said two receiving channels and for generating a control voltage in accordance with the difference between the automatic gain voltages applied thereto and first and second voltage controlled attenuators connected to receive the signals from said first and second receiving channels, respectively, each of said voltage controlled attenuators having a control element to which the output control voltage from said difference circuit is applied, said summing means being connected to receive the output signals from said voltage controlled attenuators, whereby said voltage controlled attenuators attenuate the signals applied thereto in accordance with the said control voltage applied to their respective control elements from said difference circuit such that the output signal from said summing means is maintained at a constant level and the signal-to-noise ratio thereof is at an optimum.

7. The diversity receiver of claim **6** wherein the attenuation ratios of said first and second voltage controlled attenuators have the following identities:

$$a_1=\frac{S_o/S_i}{1+\overline{N}_1^2/\overline{N}_2^2}$$

and

$$a_2=\frac{S_o/S_i}{1+\overline{N}_2^2/\overline{N}_1^2}$$

respectively, where:

a_1=voltage attenuation ratio of said first voltage controlled attenuator
a_2=voltage attenuation ratio of said second voltage controlled attenuator
S_o=output signal from said summing means
S_i=signal voltage from either of said receiving channels
$\overline{N}_1^2$=time average effective noise power from said first receiving channel
$\overline{N}_2^2$=time average effective noise power from said second receiving channel.

8. The diversity system of claim **7** wherein each of said voltage controlled attenuators comprises a logarithmic silicon diode operating as said control element, an input circuit including an input resistor for coupling the signal from the receiving channel with which it is associated to said diode, a control signal feeding circuit for coupling said control voltage to said diode, and an output circuit for coupling the attenuated output signal from said diode to said summing means, whereby the attenuation of said signal from said receiving channel is varied in accordance with said control voltage.

9. The diversity system of claim **8** wherein the signal S_i from either of said receiving channels is equal in amplitude to the combined output signal S_o from said summing means, wherein the small-signal AC resistance of said logarithmic silicon diode is defined as follows:

$$R_s=R_o10^{-K_1E}$$

where:

E is said control voltage applied to said silicon diode from said difference circuit,
R_s is the small-signal AC resistance of said silicon diode, and
K_1 and R_o are diode constant parameters describing said diode, R_o specifically being the value of AC resistance for zero control voltage; and

wherein the resistance (R) of said input resistor is chosen to be equal to R_o, said control voltage E is proportional to the difference between said summed automatic gain control voltage in decibels by a proportionality constant K_2, and K_2 is chosen to be equal to $\frac{1}{10}K_1$.

10. A pre-detection optimum diversity receiver comprising: first and second receiving channels having equal effective receiver noise voltages; an antenna connected to said first receiving channel; another antenna, orthogonally polarized with respect to said aforementioned antenna, connected to said second receiving channel; automatic gain control means included in said receiving channels for generating automatic gain control voltages proportional to the signal-to-noise ratios of the signals passed thereby; means cooperating with said automatic gain control means for modifying said signals of said channels so that the output signals from said receiving channels are equal in amplitude and phase coherent; a weighting means, said weighting means including first and second voltage controlled attenuators connected to said first and second receiving channels, respectively, and a difference circuit connected to automatic gain control means for combining said automatic gain control voltages to produce a control voltage, said voltage controlled attenuators each having a control element to which is coupled said control voltage, whereby the impedances of said first and second attenuators are varied such that the signal from said attenuator having the lower signal-to-noise ratio is attenuated a greater amount than the signal from the one having the higher signal-to-noise ratio; and summing means connected to said weighting means for receiving the attenuated signals from said voltage controlled attenuators and combining them, whereby, by the action of said weighting means the output from said summing means is a signal having a maximum signal-to-noise ratio and a constant amplitude.

11. The diversity receiver of claim **10** wherein the attenuation ratios of said first and second voltage controlled attenuators have the following identities:

$$a_1=\frac{S_o/S_i}{1+\overline{N}_1^2/\overline{N}_2^2}$$

and

$$a_2=\frac{S_o/S_i}{1+\overline{N}_2^2/\overline{N}_1^2}$$

respectively, where:

a_1=voltage attenuation ratio of said first voltage controlled attenuator

a_2=voltage attenuation ratio of said second voltage controlled attenuator

S_o=output signal from said summing means

S_i=signal voltage from either of said receiving channels

$\overline{N}_1^2$=time averaged effective noise power from said first receiving channel

$\overline{N}_2^2$=time averaged effective noise power from said second receiving channel.

12. The diversity receiver of claim 11 wherein each of said voltage controlled attenuators comprises a logarithmic silicon diode operating as said control element, said logarithmic silicon diode having a small-signal AC resistance expressed as follows:

$$R_s = R_o 10^{-K_1 E}$$

where:

E is said control voltage from said difference circuit circuit and has a proportionality constant equal to $\frac{1}{10}K_1$,

R_s is the small-signal AC resistance of the silicon diode, and

K_1 and R_o are diode constant parameters describing said diode, R_o specifically being the value of AC resistance for zero control voltage;

an input resistor (R) connected between said diode and said receiving channel with which it is associated, said input resistor (R) equal to R_o; a control voltage feeding circuit connected between said diode and said difference circuit for applying said control voltage to said diode; and an output circuit connected between said diode and said summing means.

13. In a diversity receiver having first and second receiving channels and wherein each of said receiving channels has means for generating an automatic gain control voltage proportional to the signal-to-noise ratio of the signal applied thereto and additional means for modifying said signal applied thereto such that the signals derived from said receiving channels are equal in amplitude and phase coherent, the improvement comprising: a combiner including first and second voltage controlled attenuators connected to receive said signals from said first and second receiving channels, respectively, said attenuators each having a control element; a weighting network connected to receive said automatic gain control voltages from said receiving channels for producing a control voltage, said control voltage being coupled to said control elements of said voltage controlled attenuators for varying the attenuation thereof; and a summing means for receiving the output signals from said voltage controlled attenuators, whereby in accordance with said control voltage applied to said attenuators the receiving channel signal having the higher signal-to-noise ratio is attenuated less than that having the lower signal-to-noise ratio, such that the output signal from said summing circuit is maintained constant and the signal-to-noise ratio thereof is at an optimum.

14. The diversity receiver of claim 13 wherein the attenuation ratios of said first and second voltage controlled attenuators having the following identities:

$$a_1 = \frac{S_o/S_i}{1+\overline{N}_1^2/\overline{N}_2^2}$$

and

$$a_2 = \frac{S_o/S_i}{1+\overline{N}_1^2/\overline{N}_2^2}$$

respectively, where:

a_1=voltage attenuation ratio of said first voltage controlled attenuator

a_2=voltage attenuation ratio of said second voltage controlled attenuator

S_o=output signal from said summing means

S_i=signal voltage from either of said receiving channels

$\overline{N}_1^2$=time averaged effective noise power from said first receiving channel

$\overline{N}_2^2$=time averaged effective noise power from said second receiving channel.

15. In the diversity receiver system of claim 14 each of said voltage controlled attenuators of said combiner comprising: a logarithmic silicon diode operating as said control element, an input circuit including an input resistor for coupling the signal from the receiving channel with which it is associated to said diode, a control signal feeding circuit for coupling said control voltage to said diode, and an output circuit for coupling the attenuated output signal from said diode to said summing means.

16. In the diversity receiver of claim 15, said silicon diode of each of said voltage controlled attenuators having a small-signal AC resistance expressed as follows:

$$R_s = R_o 10^{-K_1 E}$$

where:

E is said control voltage from said weighting network and has a proportionality constant equal to $\frac{1}{10}K_1$,

R_s is the small-signal AC resistance of the silicon diode,

K_1 and R_o are diode constant parameters describing said diode, R_o specifically being the value of AC resistance for zero control voltage,

said input resistor having the resistance (R) thereof equal to R_o; and said control voltage E having a proportionality constant K_2 equal to $\frac{1}{10}K_1$.

17. In the diversity receiving system of claim 16, said first and second voltage controlled attenuators varying in gain in accordance with said control voltage applied to said silicon diodes thereof such that the output signal from said summing means is adjusted so that it is maintained equal to said signal applied to said first voltage controlled attenuator from said first receiving channel.

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